UNIVERSAL MASS DEPENDENCE FOR PARTICLE PRODUCTION RATES IN e^+e^-, pp AND AA COLLISIONS FROM THE QUARK-GLUON PLASMA PERSPECTIVE

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ABSTRACT

It is demonstrated that universal mass dependence for meson and baryon inclusive cross-sections advocated recently in e^+e^- annihilation and in hadronic reactions is consistent also with heavy ion collisions data and can therefore be used as a reference for quark-gluon plasma studies.

1. Introduction

The search for the new state of matter, the quark-gluon plasma (QGP), is nowadays one of the main driving forces behind the constant interest in multiparticle production processes at high energies. There is a vast literature discussing theoretical and experimental aspects of possible signals of QGP [1]. One of the possible signals of the QGP is the enhancement of strangeness production in heavy ion collisions. Interpretation of this enhancement can be, however, regarded as still a controversial one with several models proposed for the explanation of existing data which fall, roughly speaking, into two categories:

- thermal models, including both those with QGP notion and models exploring the hadron gas concept [2,3,4];
- models using, in one or another form, the concept of colour string formation and its subsequent fragmentation [5,6,7,8,a].

We shall present here an observation which in our opinion can serve as an additional check for possible models of multiparticle production in heavy ion collisons, in particular to discriminate between the two classes of models mentioned above with the ultimate aim to help in clarifying further the problem of existence of the QGP.

2. Universal mass dependence in e^+e^- annihilations and hadronic reactions

That observation is the apparent *universal mass dependence for meson and baryon*

[a]There are attempts to provide a model *interpolating*, in a sense, between both alternatives presented here, by starting with strings and thermalizing them afterwards in such a way that particles are finally produced from a kind of thermal fireball, cf. Ref. [6].

inclusive cross-sections first observed in e^+e^- annihilations [9] and recently confirmed also in hadronic reactions [10]. It was demonstrated there that data on inclusive particle production cross-sections (or rates of particles) in high energy interactions follow the very simple formula:

$$\sigma_{incl} = a \frac{2J+1}{2I_m+1} \exp\left(-bM^2\right) \tag{1}$$

where J denotes the spin, I_m a modified isospin and M the mass of the produced particle. Two points should be stressed here:

- the cross section depends on the mass of produced particle *quadratically* and
- it contains the spin $(2J+1)$ and (modified) isospin $(2I_m+1)$ weighting factors accounting roughly speaking for non-observed states [b].

In Fig. 1 (taken from [9]) one can see very clearly that, except of pions, all scalar and vector mesons put together with octet and decuplet baryons for the LEP energy lie, when plotted as a function of M^2, on one straight line with a slope parameter

$$b \;=\; 3.9\ (\mathrm{GeV/c^2})^{-2}. \tag{2}$$

The important thing here is that:

- the same value of the slope parameter b is observed at both PEP/PETRA and at LEP energies and that
- only the normalization constant a is energy dependent.

As one can see in Fig. 1:

- pions evidently do not follow this simple rule (most probably as a result of the contribution of pions from the decays of high mass resonances, but there are also other more speculative possibilities mentioned by the authors of [9]);
- there is a deviation from this universal curve observed for the heaviest particles produced at lower, i.e., PEP/PETRA, energy (cf., however, discussion in [9]); this fact will be important in our further discussion below.

The word *universal* used above refers to the fact that (almost) all species of produced particles lie on the universal curve with the same slope. But so far the figures presented here refer to only one type of reactions, although the most elementary one: $e^+e^- \to hadrons$. A follow-up question rises then immediately: *Does this universality hold also for hadronic collisions?*

There are, however, two difficulties one has to be aware of concerning hadronic collisions:

[b] Cf. refs. [9,10] for detailed explanation of these weighting factors.

(i) the available data are scarce and with large systematic errors due to the well known experimental difficulties in the identification of particles and in the measurement of inclusive cross-sections for hadronic resonances in a many particle environment;

(ii) there is a difference between e^+e^- annihilations and pp collisions: in hadronic reactions the quantum numbers of the initial state are different from those of the vacuum state. It leads to initial asymmetry which, for instance, in pp interactions manifests itself in the enhancement of the production of baryon resonances in comparison to antibaryons because there are already two baryons present in the initial state [c].

The following sets of data were considered in [10] and are shown in Fig. 2 (taken from [10]): (i) - the analysis of pp collisions done by LEBC-EHC Collab. for $p_{LAB} = 400$ GeV/c (corresponding to center of mass energy $\sqrt{s} = 27.4$ GeV [11]), (ii) - Fermilab 30-inch bubble chamber data at $p_{LAB} = 405$ GeV/c ($\sqrt{s} = 27.6$ GeV) [12] and (iii) - results from two ISR experiments: the SFM and ACCHMN Collab. at $\sqrt{s} = 53$ GeV [13,d]. Only the results for antibaryons and neutral or negative mesons were considered because these particles are produced mainly from the quark-antiquark or diquark-antidiquark pairs created during string fragmentation and therefore should not be sensitive to the possible initial state biases. The inclusive cross-section for antiprotons at $\sqrt{s} = 53$ GeV was calculated from the compilation [14].

Fig. 2 shows that the answer to the question posed above is positive. For low mass particles we indeed observe the same regularity in meson and baryon production also in high energy hadron-hadron collisions and the corrected inclusive cross-sections are consistent with the behaviour decribed by eq.(1) with the slope parameter b taken from e^+e^- annihilation data.

The observation of *universal* (i.e., M^2) behaviour of the particle production rates points strongly towards the common fragmentation/production mechanism operating in both types of collisions, namely to hadron states being predominantly produced locally in string fragmentation irrespective of the configuration of the strings in various processes. To further check this conjecture one would need, however, precise data on meson and (anti)baryon inclusive cross-sections both for $\bar{p}p$ CERN Collider and Fermilab Tevatron. Only then strings produced in hadronic collisions will have masses comparable to those seen in e^+e^- annihilations at LEP. Hadronic data presented in

[c]In fact, one can argue that there is also the third difficulty expressed by the fact that, as far as strings are concerned, their configurations are more complicated in hadronic collisions than in the e^+e^- annihilations. We can expect, however, that some features of the local hadron production will be similar in both types of processes.

[d]The results from the two ISR experiments for the production of high mass resonances are not consistent and for $K^\star(1430)$ they differ by as much as an order of magnitude!

Fig. 2 correspond in this respect to e^+e^- annihilations at the PEP/PETRA energies where, as we have already noticed before, an upward deviation from the universality has been observed. We can attribute it to the final energy effect originating from the non-universal (i.e., flavour dependent) fragmentation of the ends of short strings. In hadronic collisions we have also contributions from diffractive excitations.

3. Universal mass dependence for particle production rates from the Quark-Gluon Plasma perspective

Encouraged by the analysis presented so far one can finally ask *whether the similar universality can be found also in the most complex multiparticle production processes, namely heavy ion collisions?*

Such universal dependence, *quadratic* in the masses of produced secondaries, points strongly towards particles being produced locally in colour string fragmentation [15] rather then from any kind of locally equilibrated (thermally and/or chemically) clusters or fireballs which would lead to $\exp(-\beta M)$ or $\exp(-\beta\langle M_T\rangle)$ factors instead (with β being an inverse temperature of the local thermal equilibrium and $\langle M_T\rangle$ a mean transverse mass) [16]. In this case from the tunneling phenomenon $b = \pi/\kappa$ and can be interpreted as a measure of the colour field strength κ in strings.

As far as the QGP is concerned, its production must *by definition* be connected with some sort of local thermal and chemical equilibrium taking place on the level of quarks and gluons. Therefore, from the point of view of the analysis presented here, in high energy heavy ion collisions one should observe a departure from the universal behaviour given by eq.(1) towards the formula with the linear mass dependence expected in thermal models. This is the main point of this presentation. We shall therefore check the existing data on particle production in heavy ion collisions for this possibility. We can hope to differentiate in this way between the two types of models mentioned at the beginning, only one of which admit the presence of the QGP.

In Fig. 3 we present the available results for particle production rates with $(2I_m + 1)/(2J + 1)$ weights accounted for in, respectively, $S + S$ and $S + Ag$ collisions at 200 GeV/nucleon and compare them with the dependence given by eq.(1) with the slope parameter (eq.(2)) taken from the e^+e^- annihilation data fit and normalized to the weighted kaon production rates. The data points for π^-, K^- and $\bar{\Lambda}$ production rates for central collisions in full phase space are from [17]. The data for $\bar{p}$ are calculated from the ratios $\bar{\Lambda}/\bar{p} = 1.5 \pm 0.5$ (for $S + S$ collisions) and 0.8 ± 0.25 (for the $S + Ag$) obtained from the fit to the corresponding central rapidity regions [18].

Notice that we again face here the same difficulty as in the case of hadronic collisions: because, contrary to the e^+e^- annihilation case, quantum numbers of the initial state are different from those of the vacuum state, we have to use only the measured rates for antibaryons and neutral or negative mesons. It can be seen that, again apart from pions, the universality of particle production observed in e^+e^- and in hadronic reactions holds also here (up to the production of $\bar{\Lambda}$, which is the highest mass state available at present for such analysis [e]). The slight deviation from the universal curve for $\bar{\Lambda}$ can be observed only for heavier nuclear targets.

Taking therefore the dependence (1) as the reference for particle production rates we can conclude that the production of $\bar{\Lambda}$ does not point toward the necessity of introduction of the thermal models (where QGP can be possibly found). Data for heavier strange antibaryons will be crucial here as they will tell us whether the observed universality in M^2 extends also to higher mass states or we shall see the first signs of an upward deviation. However, in order for such data to be decisive we have to wait for much higher energies then those available today. The point is that any upward deviation which looks like an outset of "thermal" (i.e., linear in mass M) dependence can be at present energies linked in a natural way to the deviations seen already in e^+e^- annihilation at lower energies (cf. Fig. 1) and in proton-proton scattering (cf. Fig. 2). One could then argue that at present energies only strings of relatively low masses are formed in the elementary processes constituting a nuclear collision. This in turn would result in the upward departure from the universality for high mass hadrons due to the predominant contributions from the non-universal (i.e., flavour dependent) fragmentation of the ends of strings taking over its universal breaking.

This explanation corresponds to the (again non thermal and surely non QGP) mechanism proposed recently in [8]. Its characteristic feature is that, according to results of [9], it should decrease with increasing energies. Also string models operating with colour rope dynamics [5], what results in smaller $b \sim 1/\kappa$, should be able to cope with such deviation from the universality. The same is true for new versions of *VENUS* [6] and *DTU* [7] models using string fusion concepts. This is a way of introduction of some collective production mechanisms without any reference to QGP. Therefore experiments at higher energies measuring very precisely yields of all secondaries should tell us which proposition is the correct one.

The weighted values for the pion production rates lie much higher then predicted. The same effect is observed in e^+e^- annihilations and in proton-proton collisions. A compelling explanation for this effect is the contribution of pions from the decays

[e] Data for $\bar{\Xi}$ are obtained only in the higher transverse momentum region $1.0 < p_T < 2.5$ GeV/c [19] and those for $\bar{\Omega}$ production available so far are in the form unsuitable for the analysis presented here [18].

of high mass resonances in addition to the direct pion production. From the QGP point of view mesons, in particular pions, provide the bulk of the observed entropy [20]. The similar behaviour of pion production rates observed in all reactions considered here poses therefore an additional challenge to the specifically QGP-type (or thermal) oriented explanations for the copious pion production in heavy ion collisions [21].

In conclusion:

- We have shown that the observed universality in the mass dependence of the particle production rates can serve as an additional useful tool for differentiating between multiparticle production mechanisms. As in the hadronic case, the higher energy data for heavy ion collisions will be of utmost interest here.

- If the observed universality continues and extends to even heavier particles (as it is observed in e^+e^- annihilations at LEP energies) it will be difficult for thermal models to account for such behaviour [f].

- If, on the other hand, with growing energy and/or masses of colliding nuclei this universality will break down even for lighter particles, it would mean that some collective effects in the production processes start to dominate; in this case thermal models (containing possibly also QGP) will be the most effective ones in description of this phenomenon.

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[f] There are attempts to fit the particle rates in e^+e^- annihilation processes using a thermal model, cf., for example Ref.[22]. However, it does not provide such universal behaviour as the one presented here and was not tested in all three types of collisions.

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Figure Captions:

Fig. 1 Production rates of pseudoscalar and vector mesons and octet and decuplet baryons at LEP (a) and PETRA/PEP energies (b), weighted with the $(2I_m + 1)/(2J+1)$ factor, as a function of particle mass squared. The line shows the result of the fit to the eq.(1).

Fig. 2 Inclusive cross-sections of mesons and antibaryons for pp collisions at $\sqrt{s} = 27.4$ GeV (a) and 53 GeV (b), weighted with the $(2I_m + 1)/(2J+1)$ factor, as a function of particle mass squared. The lines in both figures show the eq.(1) dependence with the slope parameter the same as in Fig. 1 and given by eq.(2).

Fig. 3 Particle rates for negative and neutral mesons and antibaryons produced in central $S+S$ collisions (a) and in central $S+Ag$ collisions (b) (both at the energy 200 GeV/nucleon) as a function of particle mass squared compared with the fit from the e^+e^- annihilation process.